

DEVELOPMENT OF STRUCTURAL HEALTH MANAGEMENT TECHNOLOGY FOR AEROSPACE VEHICLES

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ABSTRACT

As part of the overall goal of developing Integrated Vehicle Health Management (IVHM) systems for aerospace vehicles, NASA has focused considerable resources on the development of technologies for Structural Health Management (SHM). The motivations for these efforts are to increase the safety and reliability of aerospace structural systems, while at the same time decreasing operating and maintenance costs. Research and development of SHM technologies has been supported under a variety of programs for both aircraft and spacecraft including the Space Launch Initiative, X-33, Next Generation Launch Technology, and Aviation Safety Program. The major focus of much of the research to date has been on the development and testing of sensor technologies. A wide range of sensor technologies are under consideration including fiber-optic sensors, active and passive acoustic sensors, electromagnetic sensors, wireless sensing systems, MEMS, and nanosensors. Because of their numerous advantages for aerospace applications, most notably being extremely light weight, fiber-optic sensors are one of the leading candidates and have received considerable attention.

INTRODUCTION

The application of traditional NDE methods for on-ground inspection of aerospace vehicles contributes greatly to their safety and reliability. However, periodic inspections significantly increase operating expense and vehicle processing time. Further, the need to disassemble and reassemble structural components to allow inspections can lead to damage or degradation of the structure or auxiliary systems (e.g., electrical wiring and hydraulic lines). Perhaps, most importantly, periodic inspections cannot address the effects of unforeseen significant damage events such as the impact damage that led to the loss of the Shuttle Columbia. Such events can only be detected by on-board, real-time monitoring systems.

NASA is focusing on technology development for Integrated Vehicle Health Management (IVHM) systems to address these issues, and to meet demanding goals in increasing aerospace vehicle safety and reliability while reducing operational costs. On-board, real-time sensing systems for structural integrity assessment are central to the IVHM approach. Such sensing systems will minimize the need for periodic NDE inspections, or at least focus these inspections to specific vehicle areas where damage was indicated. Sensors comprising an IVHM system must be able to withstand harsh aerospace operating environments, while having minimal size, weight, and power requirements. Several candidate sensor technologies for use in an IVHM system are discussed in this paper. These include fiber-optic sensors, active and passive acoustic methods, remote wireless technologies, and remote non-contact sensing. Additionally, a brief discussion on IVHM system architecture is provided to illustrate the considerations given to establishing architectures capable of handling the data acquisition, processing, analysis, and storage for massive numbers of multiple sensor types.

FIBER OPTIC SENSORS

Considering the large acreage of aerospace vehicle structural elements, it is a given that extremely large numbers of sensors will be required for on-board structural integrity assessment. Fiber optic sensors have been identified as a leading candidate technology for meeting this

requirement with minimal weight penalty. Numerous sensor sites can be multiplexed along a single optical fiber, mitigating the complexity and weight inherent with the wiring required for a large number of single ended sensors. Fiber optic sensors also provide other advantages such as the ability to measure many different structural parameters of interest, immunity to electromagnetic interference (EMI), and the ability to operate over very large temperature environments.

Fiber optic sensors can be separated into two classes for discrete strain and temperature measurement: cavity-based designs and grating-based designs [1]. Cavity-based designs utilize an interferometric cavity in the fiber to create the sensor. Examples include the extrinsic Fabry-Perot interferometer (EFPI), the intrinsic or fiber Fabry-Perot interferometer (IFPI or FFPI), and all other etalon-type devices. Although such sensor designs have been utilized in a wide variety of applications such as in high temperature and EMI environments, they do not allow for multiplexing capability in a single fiber, and thus may be limited for applications requiring large number of sensors.

Grating-based designs utilize a photo- or heat-induced periodicity in the fiber core refractive index to create a sensor whose reflected or transmitted wavelength is a function of this periodicity. Grating-based sensors (e.g., Bragg gratings) can be easily multiplexed by using gratings of different wavelength as in the case of wavelength division multiplexing (WDM). Factors limiting the number of sensors in a single fiber include the limited bandwidth of the source as well as that supported by the fiber, and the range over which the physical parameter of interest is being measured.

Another grating-based system developed at NASA Langley [2,3] has the ability to multiplex hundreds or thousands of Bragg gratings (with the same wavelength) in a single fiber. The system is based on the principle of optical frequency domain reflectometry (OFDR) and essentially eliminates the bandwidth limitations imposed by the WDM technique. These sensors have been characterized against conventional strain sensors on test articles such as shown in Figure 1, demonstrating good agreement. In addition, they have been used to provide high density strain mapping on a number of structural test articles ranging from laboratory lap splice joints such as shown in Figure 2 to full scale composite wings and propellant tanks.

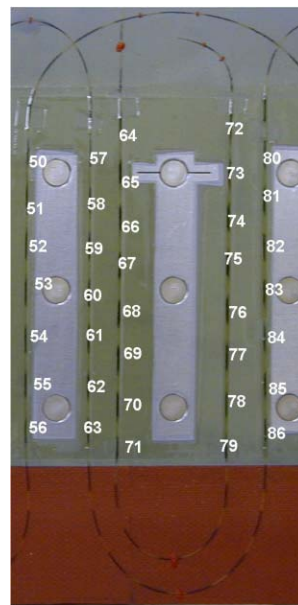
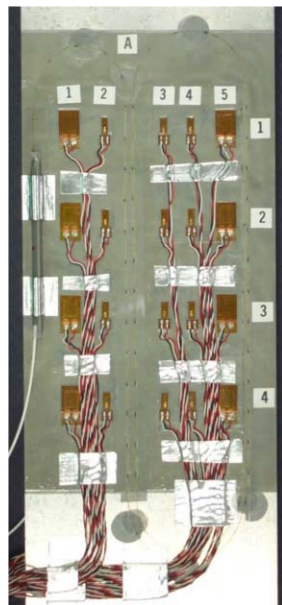


Figure 1 Mechanical test coupon instrumented with optical fiber and conventional strain gages **Figure 2** Lap splice fatigue test article with high density optical fiber sensor array.

Ongoing research areas that are critical to the practical implementation of optical fiber sensors for aerospace structures include: 1) adhesive selection and bonding procedures for surface mounting the fiber optic sensors, 2) embedded fiber optic sensor characterization at elevated and cryogenic temperatures, and 3) transverse sensitivity of fiber optic sensors. These areas will continue to be explored in future research to support aerospace vehicle requirements.

ACTIVE AND PASSIVE ACOUSTIC SENSING

Acoustic sensing, applied in both active and passive modes, is another sensor technology area receiving considerable attention. Analysis of actively transmitted acoustic signals (most often in the ultrasonic frequency range) is a conventional NDE methodology that has long been used to detect and assess damage. However, such approaches use sensors that are scanned over the structure to provide a point-by-point representation of material properties and/or damage locations. Such scanning probe approaches are not currently feasible for continuous, on-board monitoring. Therefore, the use of arrays of permanently attached or embedded ultrasonic transducers, which act dually as transmitters and receivers, is being researched. Ultrasonic signals generated by one transducer are detected by neighboring transducers within an array. Damage along paths between the transducers can be detected, and with more complex analysis methods, material along secondary propagation paths that include reflections from structural boundaries can also be evaluated. The development of the Stanford Multi-Actuator Receiver Transduction (SMART) layer is an excellent example of recent efforts in this area [4]. Ongoing areas of research in active ultrasonic sensing technology for structural health monitoring include 1) the further improvement and characterization of miniaturized, rugged, embeddable sensors, 2) analysis methodologies for optimized sensor placement to enable characterization of damage throughout the entire structure rather than just along direct propagation paths, and 3) modeling of ultrasonic guided wave propagation that occurs when such sensors are attached or embedded on thin-walled aerospace structures.

Passive acoustic monitoring, also known as acoustic emission (AE), also utilizes an array of sensors. The sensor array is used to passively monitor acoustic signals generated by damage mechanisms such as crack growth and impact damage. The loss of the Shuttle Columbia as a result of ascent impact damage to the reinforced carbon-carbon (RCC) wing leading edge has led to considerable interest in the capabilities of AE sensing of impact damage. Both low frequency accelerometers as well as high frequency, ultrasonic AE sensors were used to monitor the impact tests performed as part of the Columbia Investigation. The sensors were placed on the inward side of the leading edge spar on the RCC test article shown in Figure 3. The impact of the foam projectile, also shown in Figure 3, was readily detected and located with such acoustic sensors. Figure 4 shows the location of the eight ultrasonic sensors relative to the impact point on the RCC panels. Figure 5 shows the signals obtained from the impact. As expected since it is nearest the impact point, sensor 5 has the largest amplitude and is the first to arrive in time. Sensors more distant from the impact site have smaller amplitudes and the waves arrive later in time. Further study is ongoing to investigate the detection of hypervelocity impacts, representative of micro-meteoroid and orbital debris damage, as part of the development and implementation of an impact detection system for the Shuttle. In addition, AE sensing of impact damage is also under development for the International Space Station.



Figure 3 Impact of external tank foam insulation on a RCC leading edge test article performed as part of the Columbia Accident Investigation. Acoustic sensors were installed on the inward side of the spar to demonstrate acoustic detection and localization of impact damage.

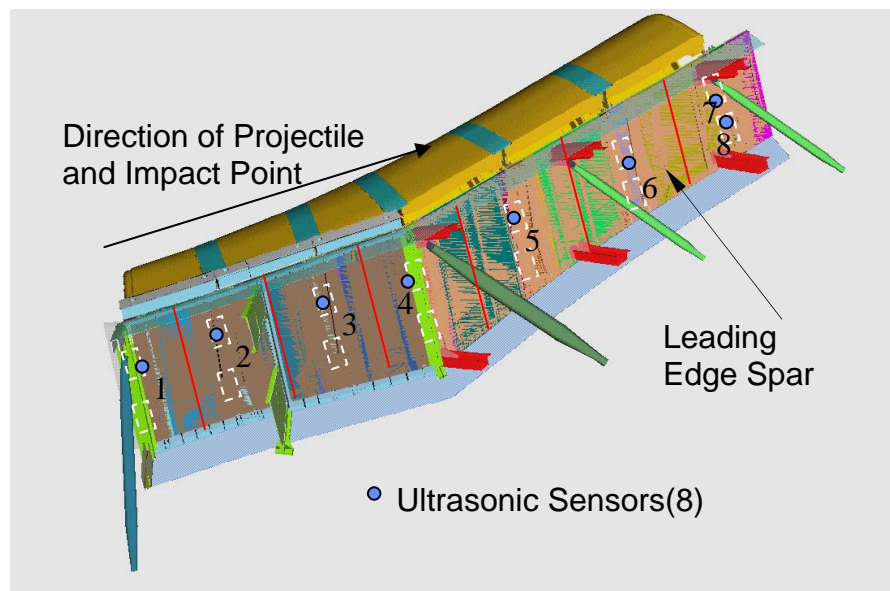


Figure 4 Diagram of RCC leading edge test article showing impact site and location of ultrasonic sensors.

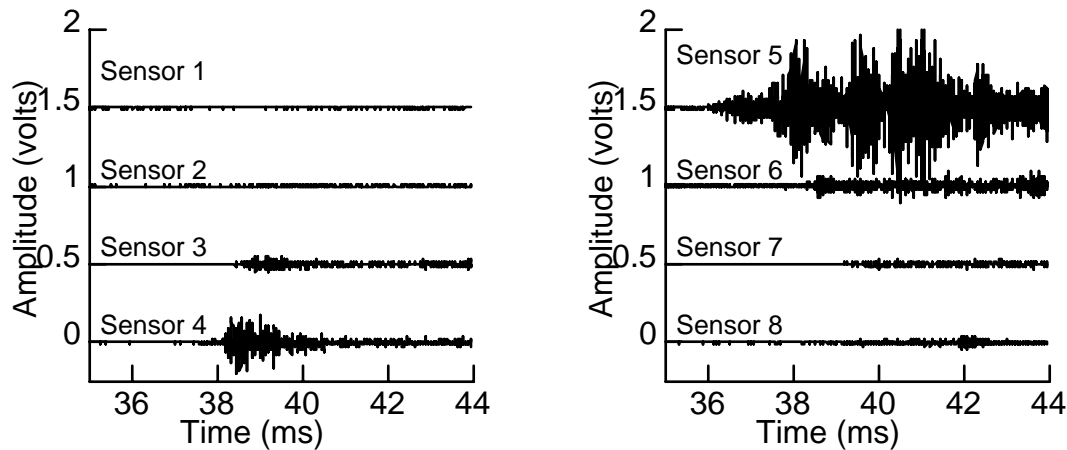


Figure 5 AE signals from foam impact on RCC leading edge panel.

Successful implementation of AE for aerospace applications will require sensors having lighter weight, increased sensitivity, and increased ruggedness over those currently available. Additionally, reductions in size, weight, and power requirements of the associated AE monitoring instrumentation are also needed. Advances in AE analysis methodologies are required to more accurately locate and identify damage, while intelligently discriminating extraneous noise from signals indicating actual damage. Ongoing efforts in this field include the development of AE multiplexing instrumentation that can miniaturize AE flight systems, the development of fiber optic AE sensors [5] and the development of Modal AE based analysis methods [6]. Another significant development is that of modeling approaches to better understand and predict AE propagation phenomena [7]. Such models are of benefit for a number of reasons to include the characterization of AE transducers, optimization of sensor placement on a structure, scaling of AE results from laboratory test coupons to full scale structures, and the development of new and automated AE data analysis methods.

WIRELESS REMOTE SENSOR SYSTEMS

Conventional sensors such as strain gages, thermocouples, and accelerometers will also be used for structural health monitoring. One major issue for such sensors is the need to route large numbers of wires to provide power and data communication. This is an especially difficult problem when retrofitting these sensors into existing structures, such as the Shuttle or the aging aircraft fleet. To address this concern, a prototype adaptable vehicle health-monitoring architecture has been developed [8] and flight tested. The architecture is self-contained and requires limited integration intrusion into existing systems, having “bolt-on/bolt-off” simplicity. There are three operational levels to the architecture: one or more Remote Data Acquisition Units (RDAU) located throughout the vehicle; a command and control unit (CCU) located within the vehicle; and, a terminal collection unit (TCU) to collect analysis results from all vehicles.

The RDAUs are multi-sensor interfaces with an on-board miniature computer, programmable digital interface, nonvolatile solid-state memory and a wireless transceiver for communication with the command and control unit. Communication is achieved by using wireless radio frequency transceivers operating at 433 MHz. The RDAUs were designed to withstand impact during aircraft landing while mounted on the main landing gear, and have been vibration tested up to an acceleration amplitude of 20 g at 2000 Hz. It was also designed to operate in non-environmentally controlled locations of the plane. The RDAU was thermally tested for temperatures ranging from -50°C to 55°C and pressure tested to simulate 50,000 ft altitude.

Vibration tests verified that the remote data acquisition unit could operate at vibration levels representative of those experienced by commercial aircraft. During vibration testing, the final acceleration amplitude was 20g at 2000 Hz. The remote data acquisition unit has an eight channel programmable digital interface, which allows the user discretion in choosing type of sensors, number of sensors, sensor sampling rate and sampling duration for each sensor. Programmable data acquisition circuitry and expert systems trained to performance baselines in each RDAU allow the architecture to be adaptable for many types of vehicles and structures. Once a suite of sensors has been chosen for each RDAU and installed on the vehicle, a baseline of acceptable vehicle performance is established from measurements acquired when the vehicle is performing correctly. Each RDAU uses an embedded expert system trained to its respective baseline

The CCU is a computer-based subsystem that provides the communications, analysis repository, and user interface functions for the RDAUs. The CCU can also serve as a power management tool by regulating when individual or combinations of RDAUs are powered. A simple radio frequency (RF) wireless network of RDAUs can be controlled from a single CCU. The TCU provides the means to autonomously retrieve vehicle analysis results from all vehicle CCUs. The TCU performs analysis on results collected from all vehicles to identify any fleet-wide anomalies (e.g., all aircraft have the same faulty bearing at a similar location). The TCU develops the final summary of the vehicle health monitoring results that gets routed to the appropriate users (e.g., maintenance workers, airlines operations, etc.).

This architecture system has been flight tested on NASA Langley's Airborne Research Integrated Experiments System (ARIES). There were 13 flight tests of the RDAU and CCU. The flight tests were performed to validate the following: the wireless radio frequency communication capabilities of the system, the hardware design, command and control, software operation, and, data acquisition, storage, and retrieval. A very rigorous test of the mechanical design was achieved by mounting the device on the left main landing gear. During the initial flight tests, none of the autonomous features had been installed. The system functioned as a remotely controlled data acquisition device. Measurements acquired during flights included take-offs, landings, vibration while gear was fully retracted, taxiing, and, touch and go landings. The flight tests demonstrated that the remotely controlled data acquisition capability worked correctly.

NON-CONTACT SENSOR SYSTEMS

Although most current visions of structural health monitoring systems are based on sensors that are attached to, or embedded within the structure, the adaptation of non-contacting measurement systems should not be ruled out. Methods such as laser vibrometry [9], shearography [10], laser ultrasound [11], and infrared thermography [12] are examples of these techniques. These methods are typically applied externally to a structure to interrogate specific vehicle components where damage may have occurred. As such, they satisfy a critical role as part of an integrated vehicle health management *system* by providing enhanced ground-based diagnostic capabilities. These techniques can thus be used to validate fault indicators or damage sites identified by the on-board sensor systems. Further, there is potential that in the future such non-contact sensor systems could be incorporated into some aerospace structural systems, such as large space platforms.

The use of structural vibration signatures as an indicator for airframe integrity is a growing field [13]. Vibration signatures are typically acquired at a single or small set of points on the aircraft surface using either a scanning laser vibrometer or accelerometers. The surface vibration data are acquired in response to an impulse force or frequency chirp applied by an excitation source at several locations about the vehicle. Comparison of the time-frequency and/or wavelet analyses of the signals obtained in *baseline* and *aged* conditions can lead to the identification of airframe cracks, disbonds, or fatigue [14-15].

Measuring the vibration signatures at only a few select points can often cause difficulties in determining the locus of damage. Therefore, it is desirable to acquire measurements at

multiple points simultaneously. This enables spatial-temporal cross correlations between the data obtained at each measurement site, yielding improved accuracy in determining the location of airframe flaws. These capabilities are currently being pursued by the development of a multi-point laser vibrometer.

A multi-point laser vibrometer is currently under development for the acquisition of vibration signatures over a two-dimensional array of measurement sites. Contrary to conventional scanning laser Doppler vibrometry (SLDV), the laser beam is not scanned from measurement site to measurement site. The time-dependent surface vibration is measured at each measurement site simultaneously so that vibration transients are preserved. Measurement site locations are generated by passing the output laser beam through a diffractive optical element, which can be fabricated to split the beam into any desired pattern with better than 90% efficiency and uniformity. Doppler-shifted scattered light is collected from each measurement location on the vibrating surface using a standard video camera lens, and mixed with reference light derived from the fundamental laser beam. The resulting light energy is intensity-modulated at the Doppler shift frequency experienced at each measurement location. The intensity-modulated light is subsequently focused to discrete sensor locations and digitized to obtain the time-dependent vibration signature. The data are further processed off-line to examine spatial-temporal cross correlation patterns for NDE purposes.

ARCHITECTURE CONSIDERATIONS

In addition to considering the types of sensors required to characterize structural integrity as part of an IVHM system, the data systems and processing architectures necessary to support such large numbers of heterogeneous sensors must also be considered. The architecture will be highly complex, as it must provide for the interrogation, digitizing, pre-processing, and archiving of massive amounts of raw signal information for consumption by modeling and analysis modules that will assess the integrity of the affected structural elements. Furthermore, since it is anticipated that a portion of the cost benefits gained through the deployment of on-board SHM systems is achieved through the elimination of certain maintenance and inspection procedures, the architecture's level of reliability must be commensurate with current regulatory guidance for assuring continued airworthiness [16, 17]. The magnitude of raw signal data, coupled with the complexity of the network interconnections and evolving diagnostic and prognostics methodologies, necessitate key architecture characteristics of scalability, robustness, flexibility, and maintainability [18].

Recognizing that architecture cannot be completely separated from application, work is underway to define a methodology that will aid in designing architectures for IVHM environments, and a layered reference architecture that facilitates scalability, robustness, flexibility, and maintainability [18, 19] is being developed. It is anticipated that a SHM architecture will support a data flow that includes real-time flight data (e.g., altitude, airspeed, accelerations, etc.) and sensor data (e.g., acoustic emission, strain, vibration, corrosion, etc.) that is tagged and conditioned (e.g., when, where, amount, rate, etc.), archived for trend analysis and usage history, then forwarded to a flight profiler for determination of phase-of-flight and maneuver. The tagged and conditioned data, coupled with flight profile, usage history, certification load data, and archived maintenance data, is then made available to the diagnostics/prognostics modules for degradation assessment.

NASA is currently giving specific emphasis to architectures supporting the deployment of Langley's OFDR fiber optic Bragg grating sensor system technology as a key sensor suite component for on-board structural health and usage monitoring. A series of simulated axial fuselage lap joints have been instrumented with Bragg gratings and tested at NASA Langley for purposes of developing an architecture concept as well as building a proof-of-concept diagnostic inference model that can infer the presence of growing fatigue cracks at affected and adjacent fasteners [20]. As a result of these preliminary tests, several key architecture areas were identified as needing further investigation including (1) reduction, representation, and archival of large data sets suitable for retrieval by current degradation and damage assessment modules, (2)

optimal techniques for increasing timeliness in demodulating the waveform, including dedicated distributed processors and analog techniques, (3) automatic identification and location of Bragg gratings within each fiber string, (4) miniaturization of components for sub-system distribution throughout the airframe, (5) fusion of fiber optic strain sensor data with other pertinent sensor information, and (6) architecture compatibility between laboratory test environments and flight-worthy avionics [21].

SUMMARY AND CONCLUSIONS

Extremely large numbers of a variety of sensor types will be necessary to provide real-time, on-board structural integrity assessment as part of an IVHM system for aerospace vehicles. These sensors will measure a multitude of parameters including strain, temperature, load, pressure, vibration, ultrasonic waves, and local chemistry. For flight applications, such sensors will need to be extremely lightweight, as well as be able to survive rugged environments. At present, fiber optic sensing is the leading candidate for such applications because of the ability to multiplex hundreds to thousands of sensors in a single fiber. Acoustic sensors, utilized in both active and passive modes, are also being studied for on-board structural health monitoring, particularly for impact detection in the wake of the Columbia tragedy. For retrofit onto existing vehicles, a remote wireless sensor architecture is being developed that can support a variety of conventional sensor types, and be bolted into locations on vehicles without having to route wires to provide communication and power. Remote, non-contacting sensor technologies are being developed for complimentary ground inspections, and possibly for on-vehicle deployment. Further, the data systems and processing architectures that will be required to support these massive numbers of diverse sensors are being considered, with special emphasis on the integration of fiber optic sensors with more conventional sensor types.

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